Jutland (Skagerrak), 100 years on - The Interior Ballistics Advances in Time

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Don Carlucci[1], Mike Nusca[2], Clive Woodley[3]

[1]U.S. Army ARDEC, RDAR-DSM, Building 94, 2nd floor, Picatinny, NJ 07806, USA
[2]U.S. Army ARL, Aberdeen Proving Ground, MD, USA
[3]QinetiQ, Fort Halstead, Sevenoaks, Kent, TN14 7BP, UK

Outline

- The situation, opposing forces technologies and the battle
- The Interior Ballistics (IB) tools available to the gun designers (expose the gaps at the time)
- IB model comparing a German 12" gun to a British 12" gun
  - Analytical
    - Describe the deficiencies of the model (this will expose gaps that were present)
  - NGEN – state of the art
    - Describe the deficiencies of the model (this will expose gaps that are still present)
- What's next in IB modeling
- What's not being addressed

Background

- May 1916
  - Central Powers – Germany, Austria-Hungary, Ottoman Empire, Bulgaria
  - Allied Powers – Great Britain, France, Imperial Russia, Italy, Serbia, Belgium, Portugal
- On the land, the opposing forces were deadlocked
  - Trench lines in France from Channel to Swiss Border
    - Battle of Verdun is ongoing
  - Italy and Austria deadlocked in the Alps and along the Isonzo River
  - Allies occupy defensive lines around Salonika, Greece
  - Germany and Austria occupy a stable, roughly North-South line in Russia
  - Ottoman Empire roughly deadlocked to varying degree within their original borders
- The Allied Navies have effectively blockaded all shipping
- German U-Boats were having a similar blockading effect on Great Britain
  - Were backing off to avoid U.S. entry into the war
- If the German High Seas Fleet can defeat the Grand Fleet (Royal Navy) and break the blockade they can potentially win the war

The Royal Navy Grand Fleet

- Larger Force
  - 28 battleships
  - 9 battlecruisers
  - 8 armoured cruisers
  - 26 light cruisers
  - 78 destroyers
  - 1 minelayer
  - 1 seaplane carrier
- Regularly reading German Naval cipher
- Steeped in tradition
- Based on experience high rate of fire is emphasized
- Line ahead standard formation
- Mine and torpedo awareness

- Design Philosophy
  - Speed offers protection
  - Ship accommodations for long cruises
  - Larger caliber guns
    - 12, 13.5, 14 and 15 inch
    - Heavier shells in all but 12 inch
  - Lower muzzle velocity
  - Ship beam fixed by Standard docking facilities
    - Lower Platform Stability
    - Fuel storage inside armored belt (coal and oil)
  - Propelling charges in silk bags
  - HE shell filler
    - Lyddite (Picric Acid)
  - AP shell filler
    - Black powder

Overall plan: Catch the bulk of the High Seas Fleet far enough from the safety of their shore bases so as to cripple it

The German High Seas Fleet

- Smaller Force
  - 16 battleships
  - 5 battlecruisers
  - 6 pre-dreadnoughts
  - 11 light cruisers
  - 61 torpedo-boats
- Under orders not to lose ships
- Newer dock facilities
- Practiced the "turn together" maneuver

- Design Philosophy
  - Protection is paramount
  - Smaller caliber guns
    - 11 and 12 inch
    - 12 inch guns had heavier shells
  - Higher muzzle velocity
  - Ship beam fixed by Kaiser Wilhelm canal
    - Greater Platform Stability
    - Fuel storage outside armored belt (coal only)
  - Propelling charges in silk bags with brass cartridge case in last increment
  - HE shell filler
    - Trotyl (TNT)
  - AP shell filler
    - Trotyl (TNT)

Overall plan: Catch a portion of the Grand Fleet and sink enough ships so as to reduce its numerical advantage

Typical Gun and Shells

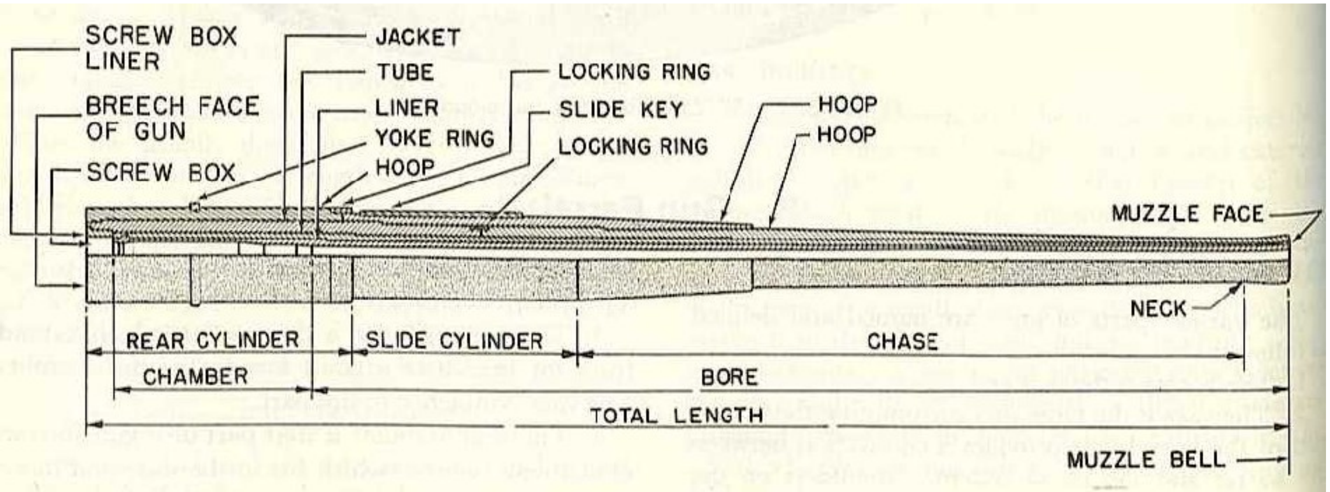
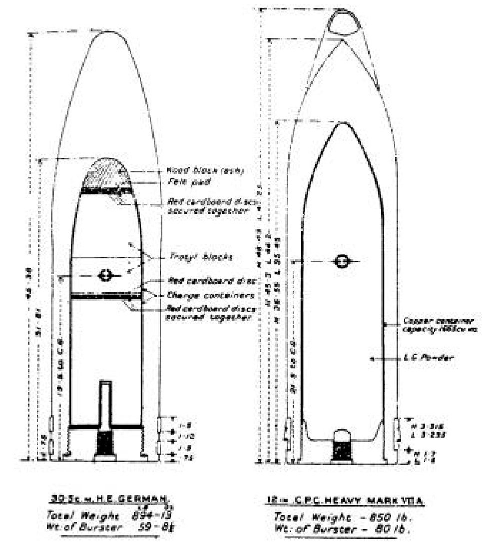
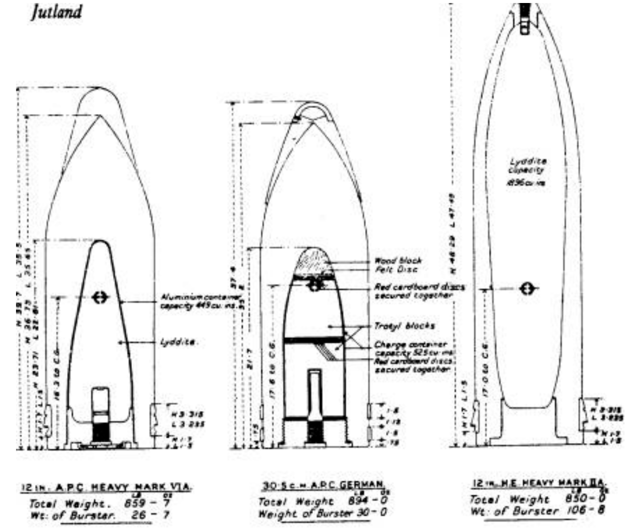


FIGURE 5B1.—Built-up gun.



From www.navweaps.com

Jutland



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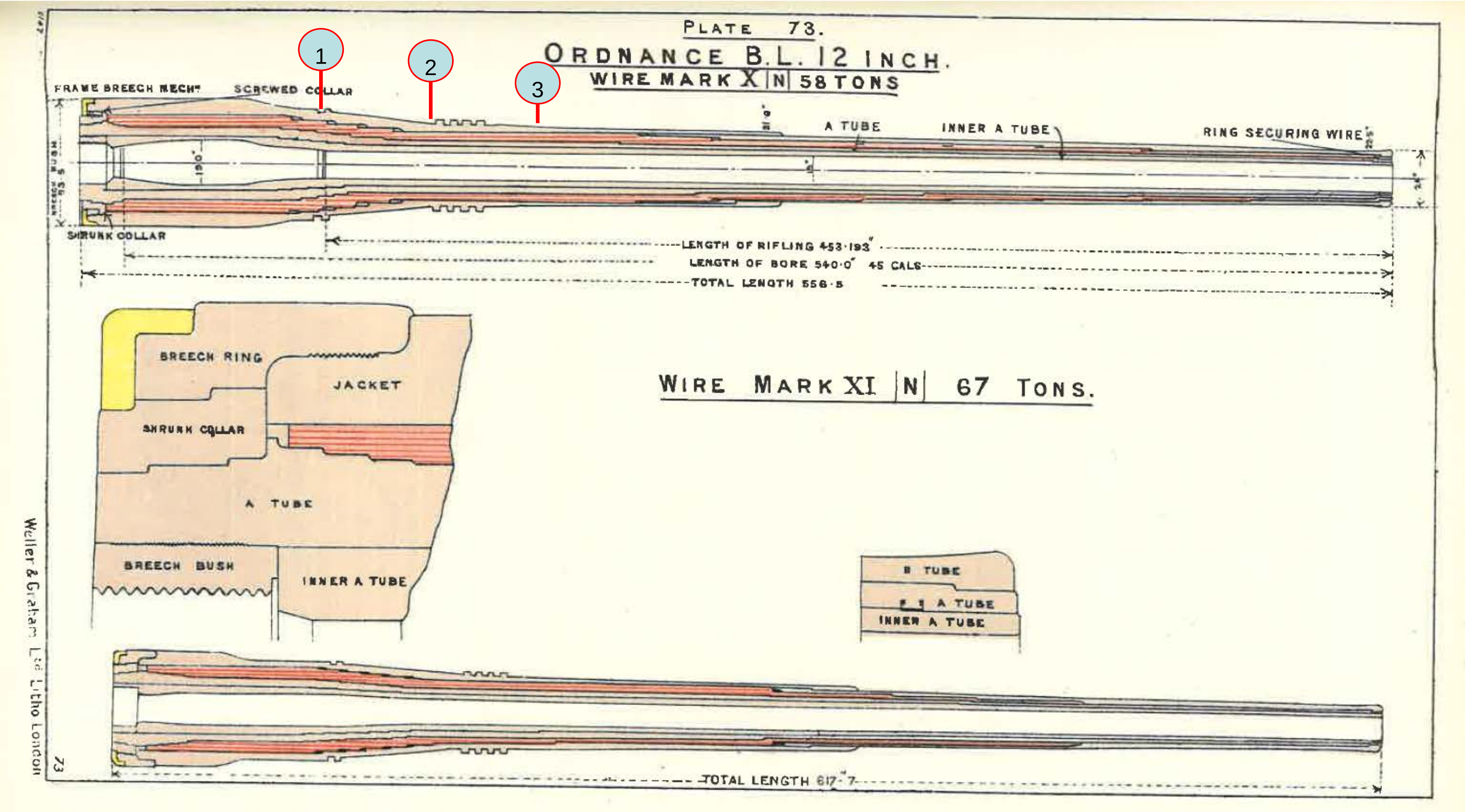
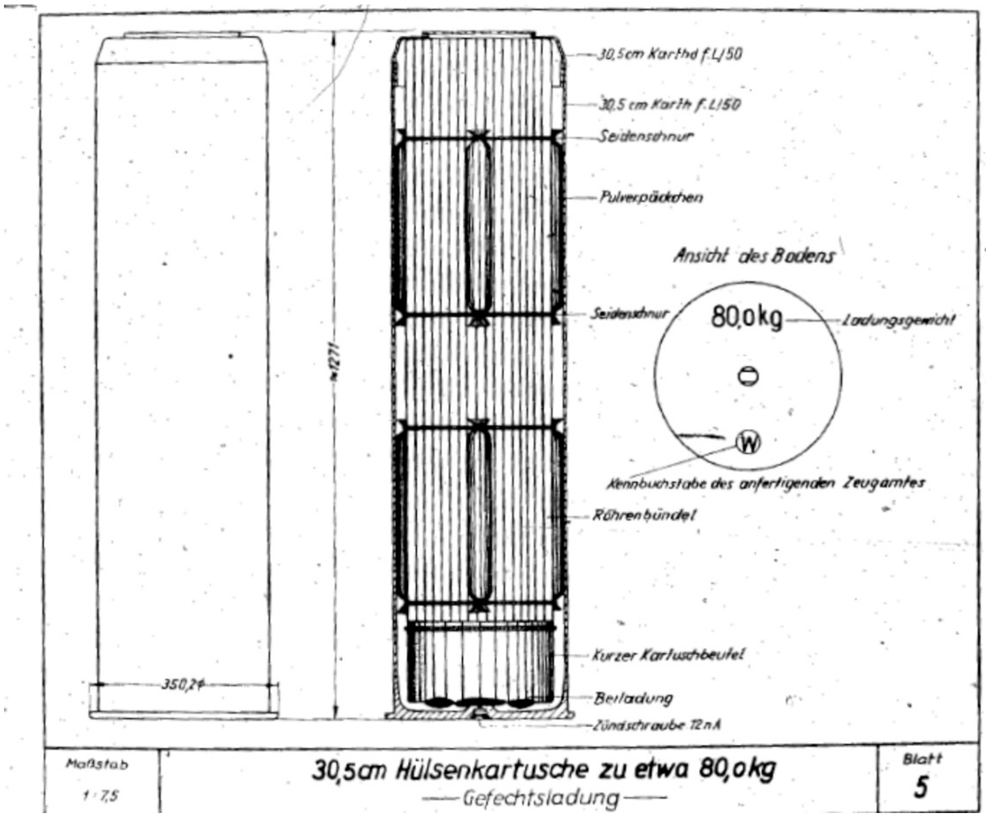
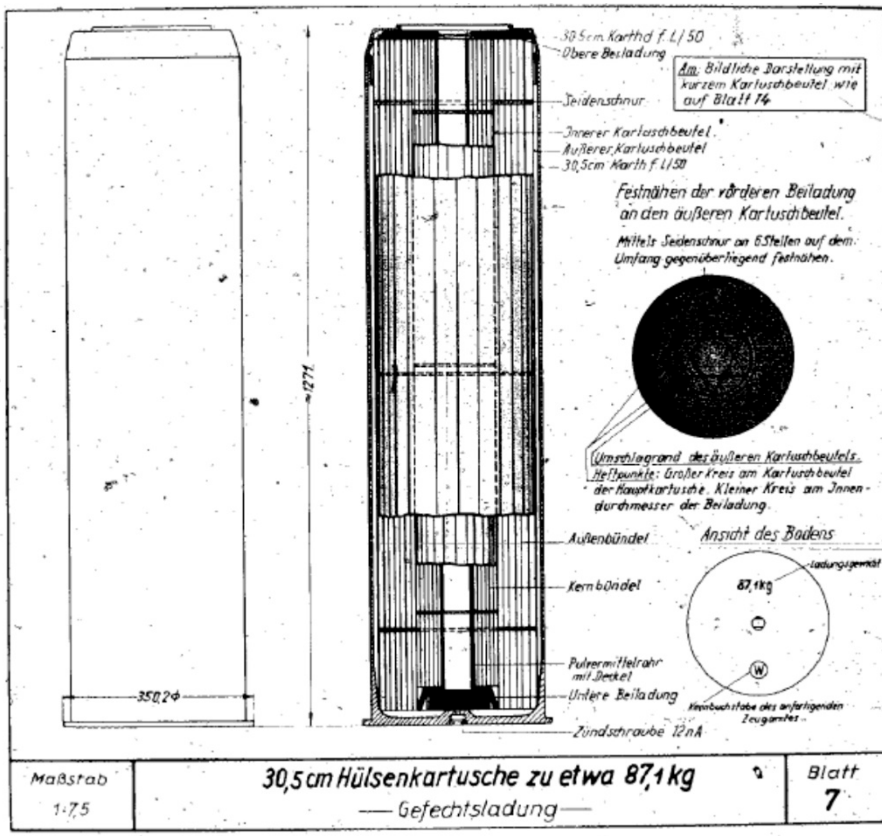
British 12 Inch Mk. X Gun



Supplied by Clive Woodley, QinetiQ through Bernard Jones, Dstl

German Propellants





Supplied by Sven Brummack, through Nathan Okun

The North Sea

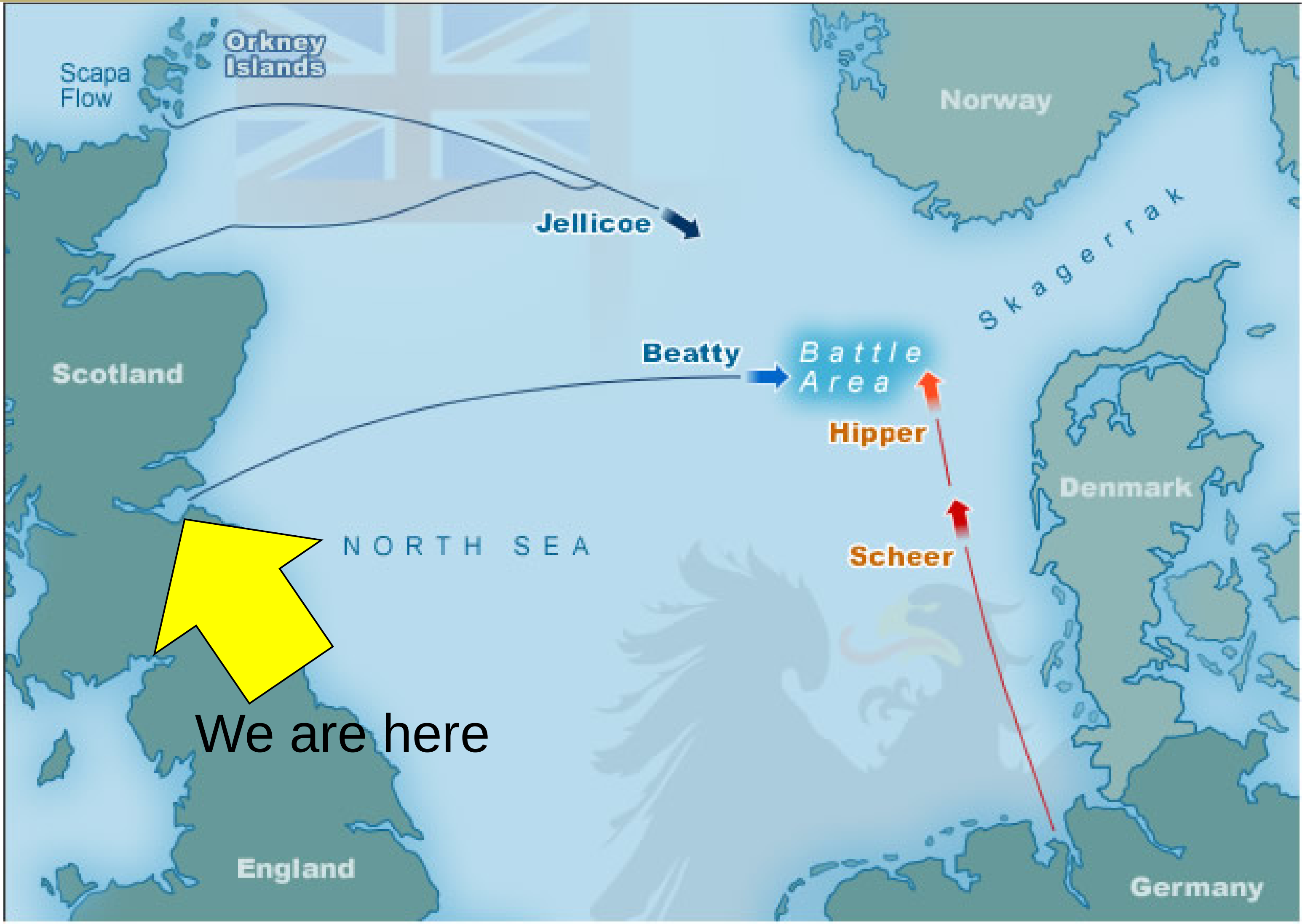


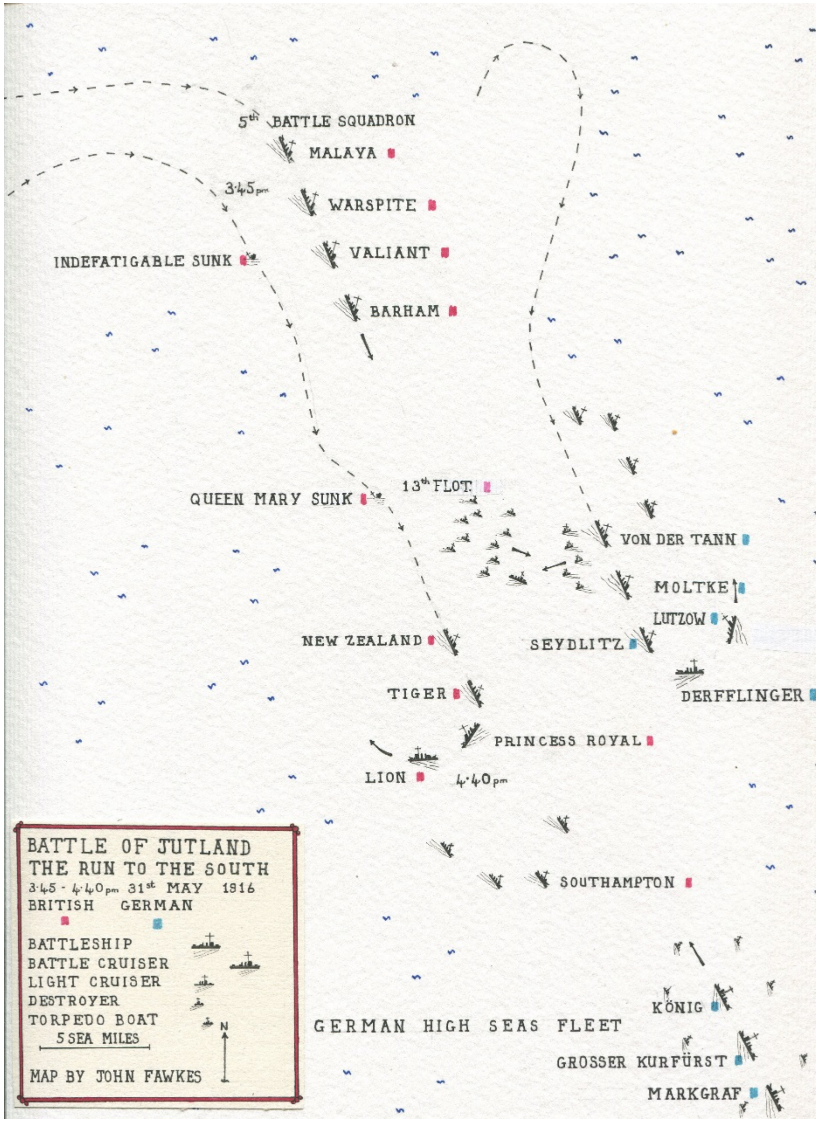
Image source: www.battle-of-jutland.com

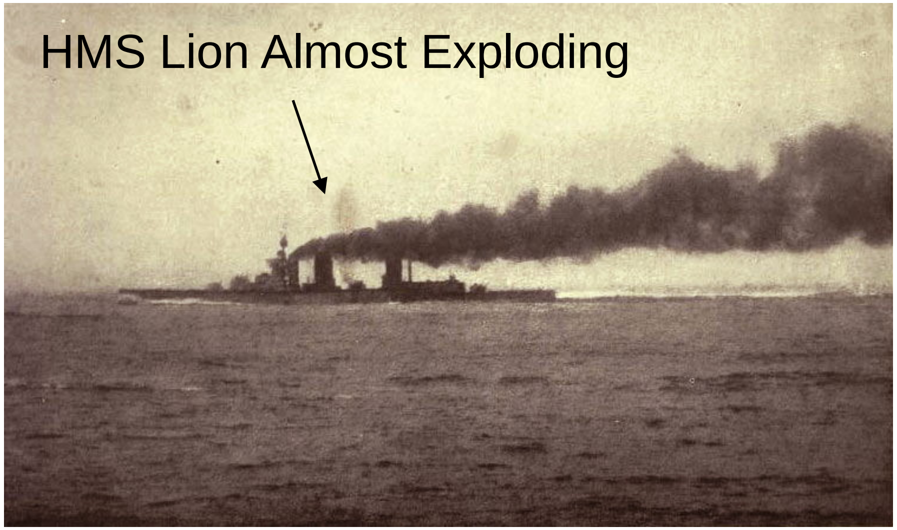
Battle Timeline

- 30 May 1916
  - British intercept signal describing the German intent to put to sea and put to sea themselves *before* the Germans
  - Poor weather limits the ability of German aerial reconnaissance but they are aware that the Grand Fleet is out through other intelligence
  - In both fleets light cruisers and destroyers scout ahead of the battlecruiser squadrons which themselves are well ahead of the main fleets
    - The British had sent some of their battlecruisers (3) North for gunnery practice but they were temporarily replaced by the 5th battle squadron (4 fast battleships with 15 inch guns)
  - At 1410 British light cruisers sight some German destroyers and chase them to the south-east
    - The British battlecruisers turn to follow but the signal to the 5th battle squadron is delayed
    - The Germans call for help and lead the British towards their Battlecruisers
  - At 1548 Both battlecruiser squadrons sight and open fire on one another at a range of 16,500 yards
    - The British were silhouetted against the low sun and the Germans hit more often
  - Both sides fired away at each other on roughly parallel courses for about an hour – moving steadily toward the rest of the High Seas Fleet coming up from the south (see next page)
    - During that time two British battlecruisers received turret hits and exploded and sank

Battle Timeline (Cont'd)

From www.britishbattles.com




HMS Lion Almost Exploding


HMS Queen Mary Exploding

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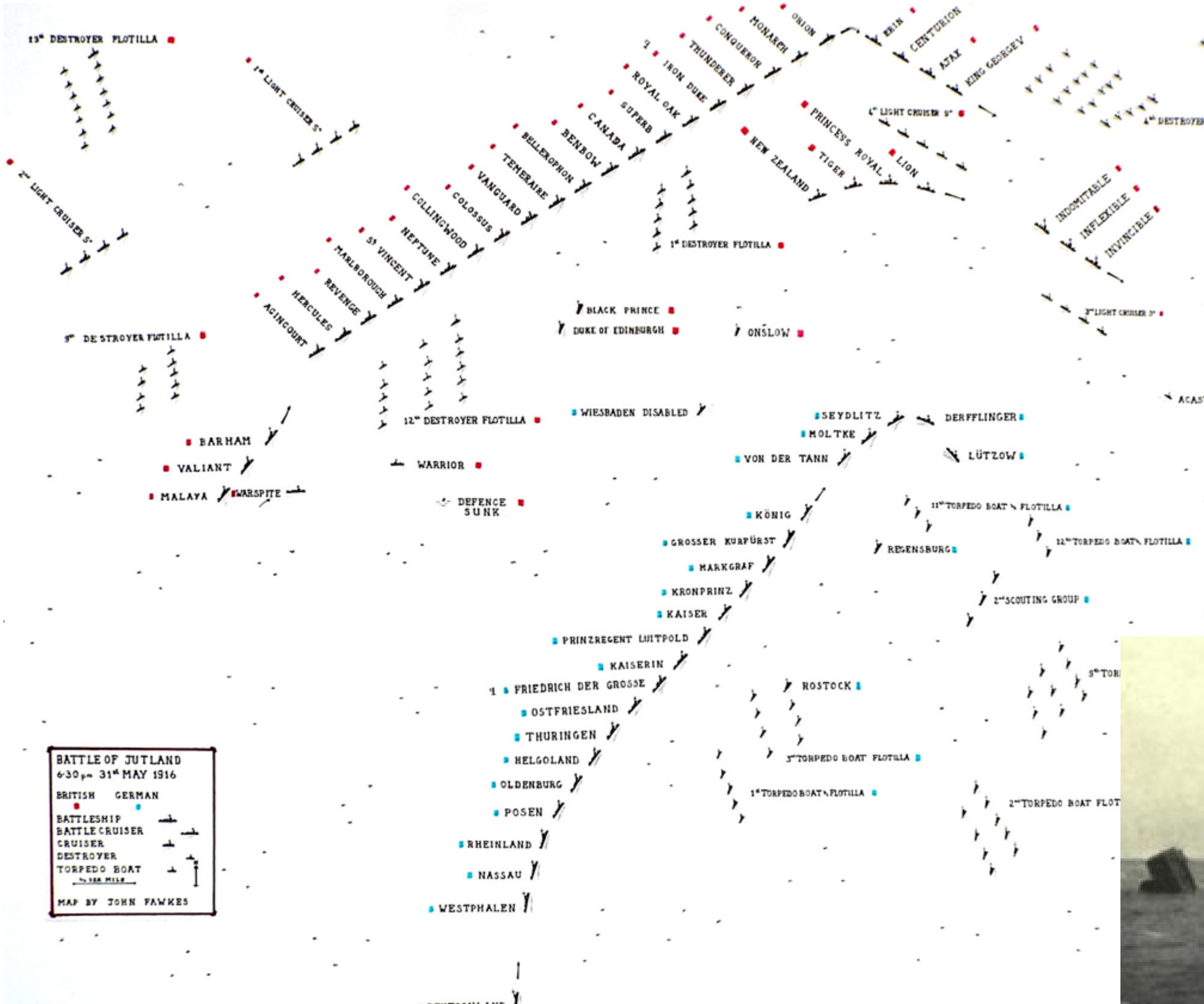
Battle Timeline (Cont'd)

- 30 May 1916
  - At 1630 both sides send destroyers and light cruisers against one another and a wild melee develops between the two opposing lines
  - The 5th battle squadron begins to fire against the German battlecruisers doing some serious damage
  - About this same time the British sight the remainder of the High Seas Fleet
  - At 1648 the British battlecruisers now turn to lead the High Seas Fleet into the arms of the Grand Fleet
    - The 5th battle squadron again misses the signal and is brought under fire of the main German force in addition to the German battlecruisers
    - It turns north under intense fire and receives serious damage
  - The German battlecruisers also turn north and give chase
  - At this point the visibility began to deteriorate
  - While the Grand Fleet Headed toward the main engagement Admiral Jellicoe sent the three battlecruisers of the 3rd battlecruiser squadron ahead since they were faster
    - They appeared out of the poor visibility from the north east and sank a German light cruiser
    - Caught by surprise, the German battlecruisers turned south again
    - All the German attention was now drawn to the 3rd Battlecruiser squadron

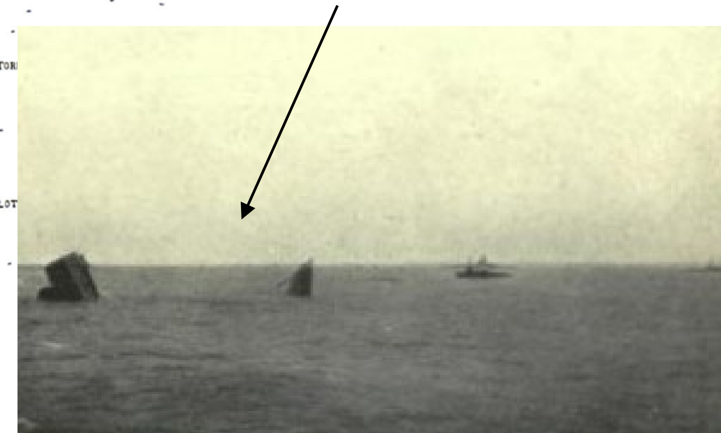
Battle Timeline (Cont'd)

- 30 May 1916
  - At 1815 Admiral Jellicoe now deployed the grand fleet from its cruising formation to the east
  - This is not noticed immediately by the Germans because of
    - Poor visibility
    - The British battlecruiser squadron was cutting in between the two opponents to get to the head of the British line
    - The 3rd battlecruiser squadron had surprised them
  - At 1833 as the Grand Fleet was nearing its full deployment into one big line the British battlecruiser Invincible was hit in the turret and exploded and sank
  - The Germans now executed a battle turn away and at 1840 firing ceased
  - At 1855 The Germans turned about again and the engagement resumed but the British were across the German "T" and the German ships suffered tremendously
  - At 1918 The Germans turned about again, this time sending their torpedo boats and four of their battlecruisers towards the British battle line – which turned away as well (See next page)
  - At 2019 sunset occurred – both fleets were headed roughly south with the Grand Fleet positioned between the Germans and the Jade basin

Grand Fleet After Deployment



HMS Invincible exploding and the aftermath



From www.britishbattles.com

RDECOM

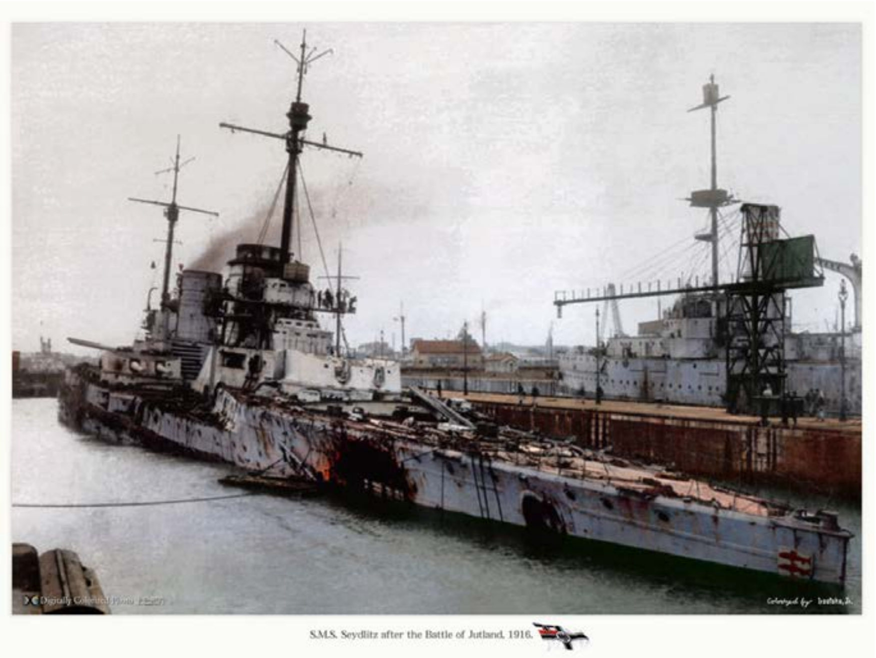
Battle Timeline (Cont'd)

- 30 May 1916
  - At 2020 a 12 minute night action occurred between both sides destroyers and light cruisers
  - At 2100 it was totally dark
  - Both sides continued towards the German base engaging sporadically throughout the night on roughly parallel courses
  - Though they did not realize it at the time, the Grand Fleet was moving quite a bit faster than the High Seas Fleet
- 31 May 1916
  - At approximately 0000 the High Seas Fleet crossed behind the British line
  - From this time until about 0300 various ships and squadrons blundered into one another resulting in short, violent actions in which several destroyers, cruisers and one German battleship were sunk
  - At 0300 the Grand Fleet turned north, concerned about night fighting canceling their numerical advantage, turning south again at daybreak
- 1 Jun 1916
  - The Grand Fleet turns north

Battle Timeline (Cont'd)

- 2 Jun 1916
  - Both sides claim victory
  - Larger tonnage of Royal Navy ships were sunk
  - Overall blockade of Germany remained in place

From www.sms-navy.com



SMS Seydlitz after the battle

From www.laststandonzombieland.com

Interior Ballistics 1916

- The weapons employed at the battle of Jutland were designed several years before
- Methods were semi-empirical, tabular or graphical
  - LeDuc, Sarrau, Moisson, Charbonnier, Bianchi, Schmitz, Ingalls, Mansell, Hezlet, etc.
- Instrumentation was copper crusher gages
  - Could only obtain peak pressure
- Electromagnetic chronograph was available to measure muzzle velocity
- With the information from the references we were able to use the LeDuc relations on the following page and obtain the plot comparison

Information on the Propellant

The following thermochemical properties for the propellants were calculated using the Russian REAL thermochemical code

Parameter	Cordite MD	RP C/12
Impetus (MJ/kg)	1.129	1.051
Flame temperature (K)	3229	3001
Molecular weight (g/mol)	23.786	23.741
Co-volume (cc/g)	1.073	1.076
Ratio of specific heats	1.230	1.238
Density (g/cc)	1.58	?

Cordite MD Composition 65% NC (13.1% nitrated), 30% NG, 5% Petroleum Jelly
Propellant geometry was solid cord (no perfs) 0.45 inches in diameter in the green state but may have shrunk to as little as 0.34 inch diameter

RP C/12 Composition 64.13% NC (11.9% nitrated), 29.77% NG, 5.75% Centralite, 0.25% Magnesium Oxide and 0.10% graphite.
Propellant geometry was single perforated - 0.71 inch OD and 0.315 inch ID

Information on the Guns

British 12-inch BL Mk. X (12-inch 45 caliber)	
Chamber length:	81.0 inches (2,057 mm)
Rifled length	453.193 inches (11,511 mm) (37.8 calibers)
Chamber volume	18,000 in^3 (295 dm^3)
Chamber pressure	18 tons/in^2
Rifling grooves	60
Rifling twist	1/30
Rifling groove depth	0.1 inches (2.54 mm)
Rifling groove width	0.467 inches (11.86 mm)
Land width	0.1612 inches (4.09 mm)
Projectile weight	850 lbs (386.4 kg)
Shell protrusion into chamber	5.015 in. max./4.735 in./min. (127.4/120.3 mm) (at 12 in. diameter)
Muzzle velocity	2746 ft/s (837 m/s)
Propelling charge	260 lbs (118.2 kg) of cordite MD

German 30.5 cm SK L/50 C/08 (12-inch 45 caliber)	
Chamber length:	99.5 inches (2,528 mm)
Rifled length	464.764 inches (11,805 mm) (38.7 calibers)
Chamber volume	12,205 in^3 (200 dm^3)
Chamber pressure	20.95 tons/in^2
Rifling grooves	88
Rifling twist	progressive 1/45 to 1/30
Rifling groove depth	0.118 inches (3.0 mm)
Rifling groove width	0.263 inches (6.68 mm)
Land width	0.1654 inches (4.20 mm)
Projectile weight	893 lbs (406 kg)
Shell protrusion into chamber	4.87 in. (123.7 mm) (mean?) (at 12 in. diameter)
Muzzle velocity	2805 ft/s (855 m/s)
Propelling charge	277 lbs (126 kg) of RP C/12 (a 201 lb (91.4 kg) main charge and a 76 lb (34.5 kg) fore charge)

LeDuc Formulae

$$a = \alpha \sqrt{\frac{c}{p} \Delta^{\frac{1}{12}}} \qquad b = \beta(1 - 0.64\Delta)\left(\frac{\mathrm{U}}{w}\right)^{3/8} \qquad V = \frac{ax}{b + x}$$

$$p = \frac{w}{g}\frac{a^2 b}{A}\frac{x}{(b + x)^3} \qquad p_{\max} = \frac{4}{27}\frac{w}{gA}\frac{a^2}{b}$$

Where

c = weight of charge in pounds.

w = weight of projectile in pounds.

Δ = density of loading.

U = chamber volume in cubic inches.

α = a constant whose value depends only on the chemical characteristics of the powder and may be taken as 6857 for U.S. Navy powder (in 1911).

β = a constant whose value (for any given kind of powder) depends only on the form and dimensions of the grain.

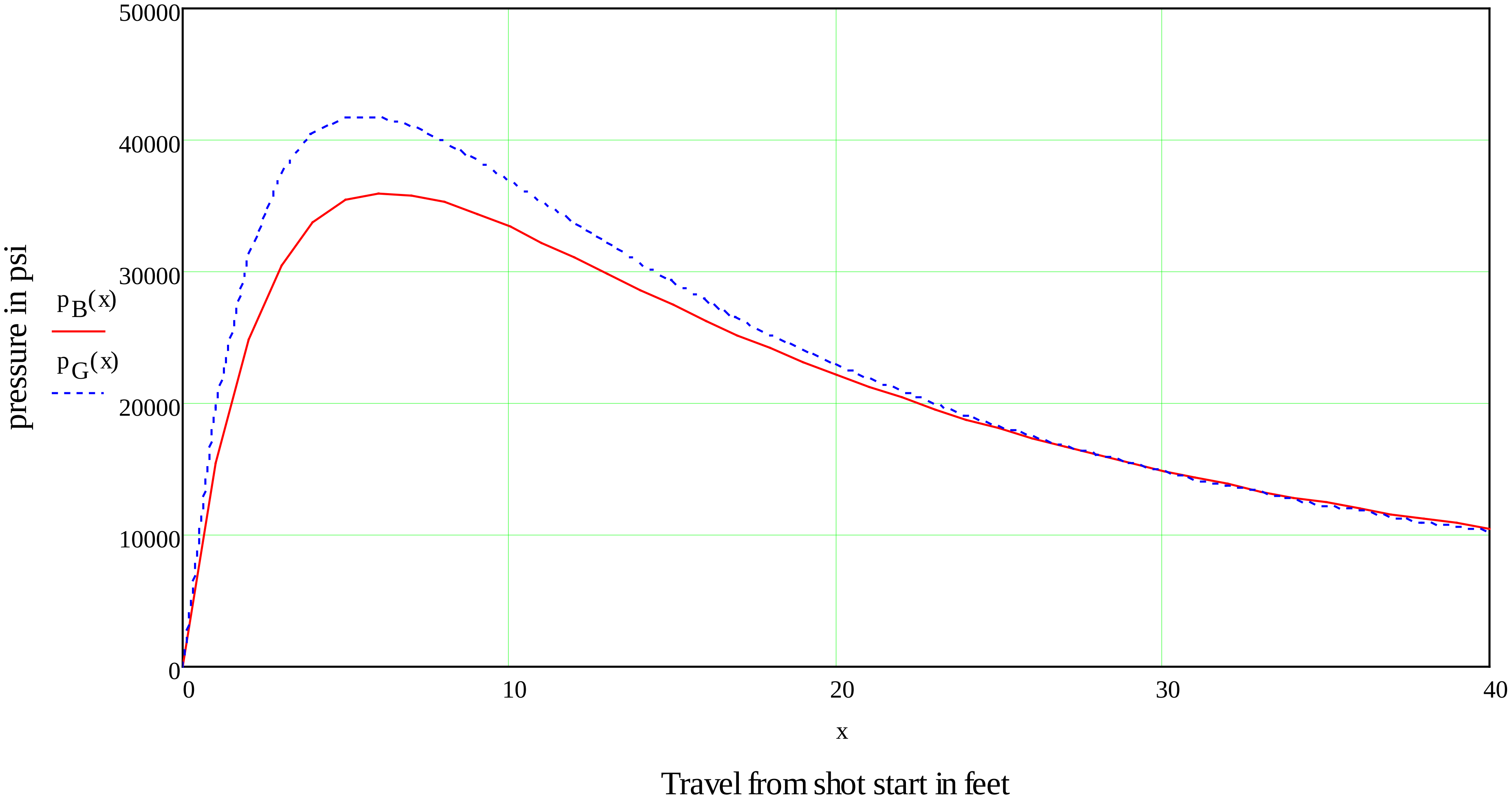
V = velocity of projectile in ft/s

x = travel of projectile in bore of gun in feet.

A = cross-section of bore in square inches.

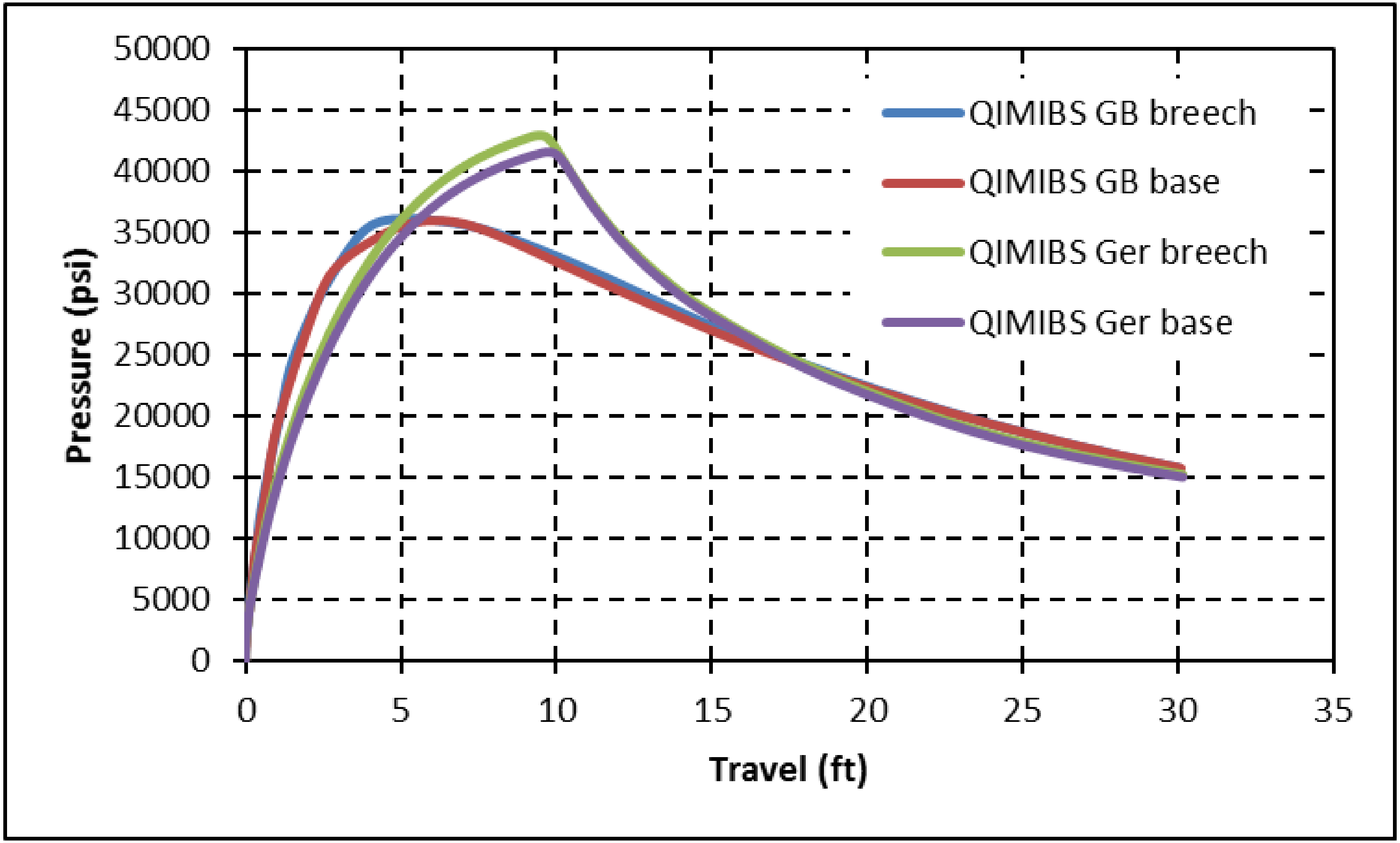
g = acceleration of gravity in ft/s^2

Comparison of 12 inch Guns



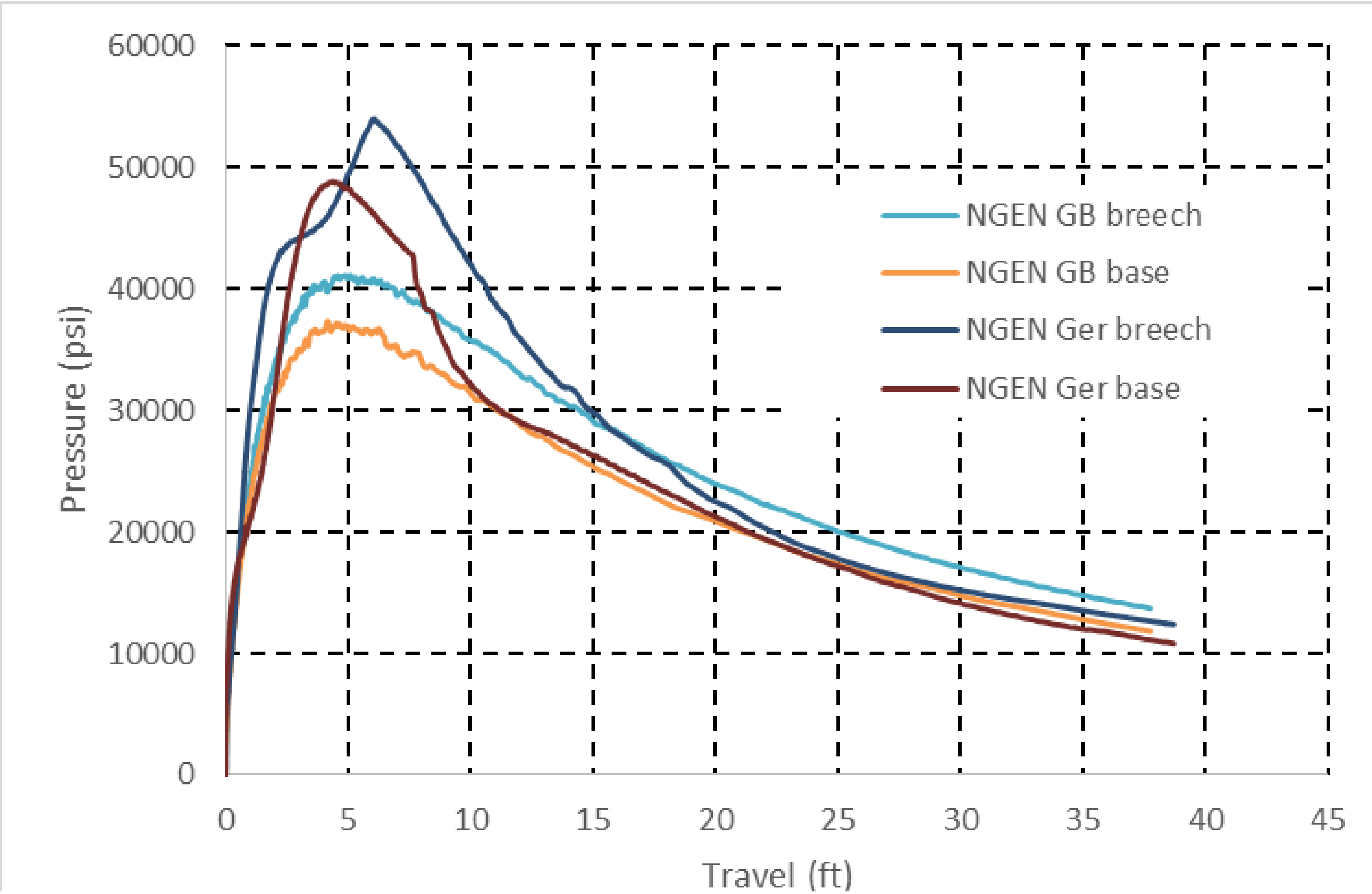
British and German 12-inch Gun performance as calculated using the LeDuc Formula

Comparison of 12 inch Guns QIMIBS



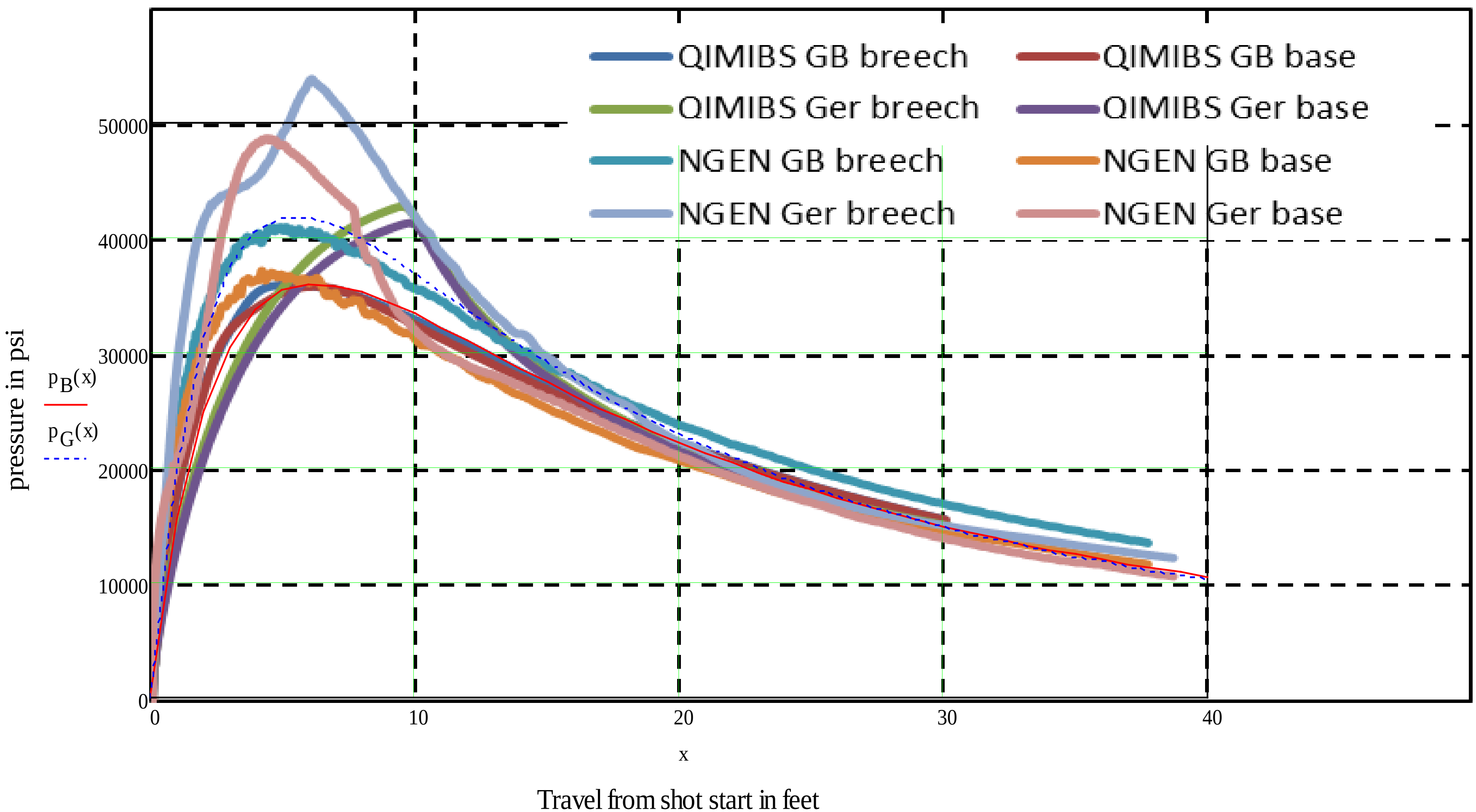
QIMIBS Model by Clive Woodley

Comparison of 12 inch Guns NGEN



NGEN Model by Mike Nusca

Overlayed Comparison of 12 inch Guns



Overlayed comparison of QIMIBS, NGEN and LeDuc

Comparison of 12 inch Guns M.V.

Method	LeDuc*	QIMIBS	NGEN
Weapon	m/s	m/s	m/s
12” Mk. 10	837	803	824
12” SK L50	855	791**	836

* Actual velocity is required for this calculation

** UK chamber volume extended by ~30 cm substituted for German chamber volume

QIMIBS Thermal Evolution in British Gun

NGEN Thermal Evolution in British Gun

NGEN Thermal Evolution in German Gun

Gun Stress Calculations

- Performed weapons stress calculations with some MAJOR simplifications
  - Used LeDuc pressure-travel curve
  - Assumed Monobloc design – built up will be stronger
  - Assumed "knocked down" fatigue strength of 76,500 psi
  - Ignored stress concentrations
  - Looked at 3 locations shown on slide 7

Location Number	Location (distance from shot start)	Pressure (lbf/in^2)	Inside Diameter (inches)	Outside Diameter (inches)
1	Origin of Rifling (0 in.)	36,000	19	48.0
2	Peak Pressure (54 in.)	36,000	12	31.9
3	Down Bore (96 in.)	34,000	12	31.9

Location Number	Von Mises Stress σ_E (lbf/in^2)	Hoop Stress $\sigma_{\theta\theta}$ (lbf/in^2)	Radial Stress σ_{rr} (lbf/in^2)	Axial Stress σ_{zz} (lbf/in^2)
1	73,939	49,377	36,000	6,689
2	72,632	47,868	36,000	5,934
3	70,912	47,868	34,000	5,604

Interior Ballistics Advances

- Better pressure transducers
  - In the gun
  - In the projectile
- Laser measurement systems for in-bore velocity measurements
- Accelerometers small enough to put in projectiles
- Computer codes
  - Structural
  - Chemical
  - Interior Ballistics
  - Coupled Codes
- Laser Bore Mapping

Interior Ballistics Unknowns

- Flame Spread Prediction
- Erosion Prediction (Chemical, Thermal, Mechanical)
  - Gun Tube
  - Rotating Band
- Ignition Behavior Prediction
  - Resulting Pressure Field
  - Pressure Waves
- Entrained Propellant Surface Regression
- Balloting Prediction
- Burn Models for New Materials and Non-traditional Propellants

Key

- Fair
- Rudimentary
- Strained
- Poor

Advanced Charges – Further Challenges

- Increasingly the interior ballistician is being asked to produce IB designs for charges that maximize the chamber volume available
  - This leads to high loading density charges with propellant/charge geometries that are highly progressive to maximize the MV
  - These advanced charges pose severe challenges to the IB modeling and expose some of the weaknesses mentioned above
- Examples
  - coated propellants, layered propellants, multiperforated propellants including monoblocks, consolidated charges, foamed propellants, etc.
- Key processes that are yet to be resolved
  - Transition in properties between coating/layers
  - Interphase drag forces (MP propellants)
  - How to represent them in many IB codes
  - How the consolidated charges break up, what physical processes occur, what is the shape of the fragments, what triggers the fracturing process
  - Porosity of the foamed propellant, size distribution, internal structure, linking between pores, strength, etc

Interior Ballistics – Back to the Future?

- Predicting the future is always dangerous but……
- Reduced order modeling will be the next BIG advancement
  - Allow few runs of highly detailed models
  - Improve time such that designers can use the data as predictive
- Are we going backwards though?
  - I say no because the faster, older codes still don't help with
    - Ignition and flame spread
    - Waves (though some do)
    - Coupled interaction with projectile and gun structure

Questions?